Physics-based Modeling for Prognostics: Application to Solenoid Valves

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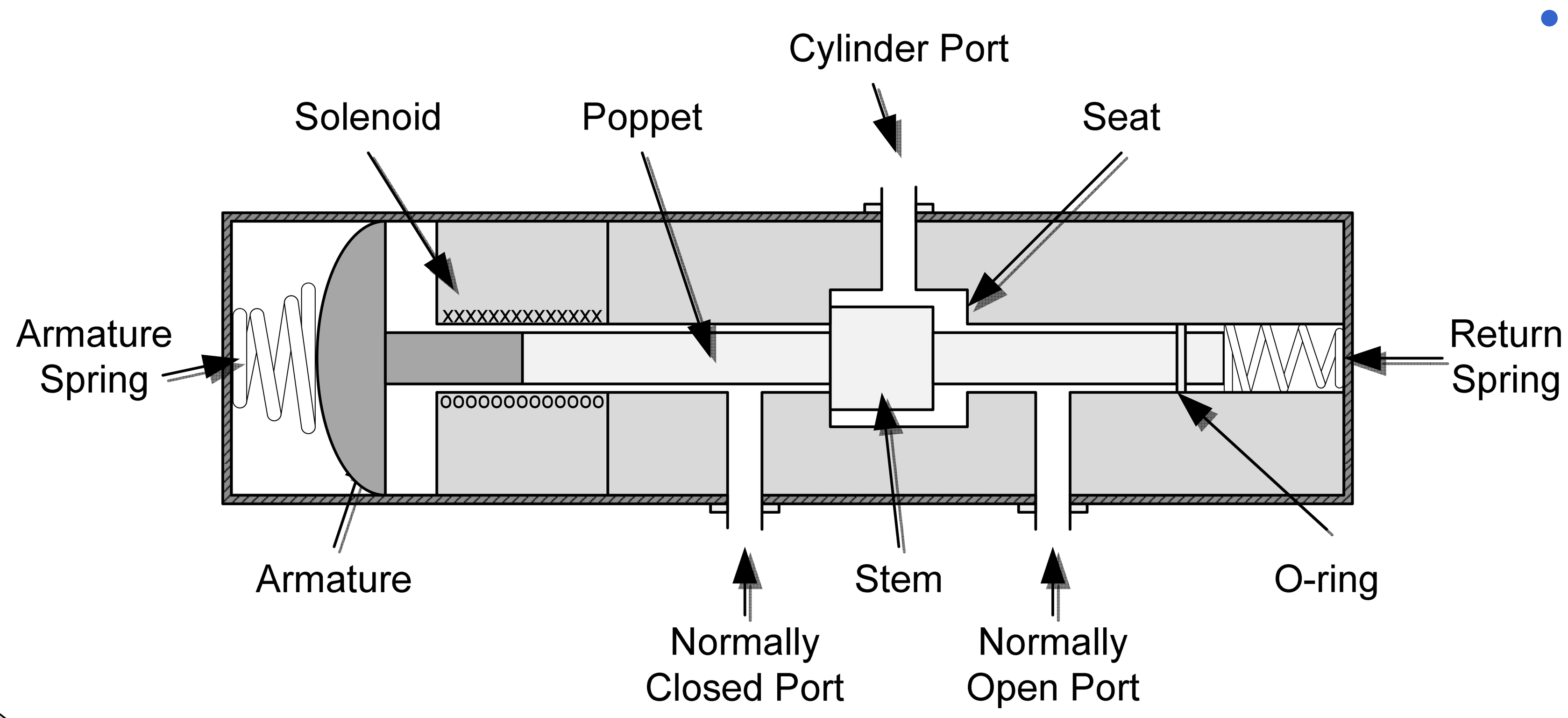
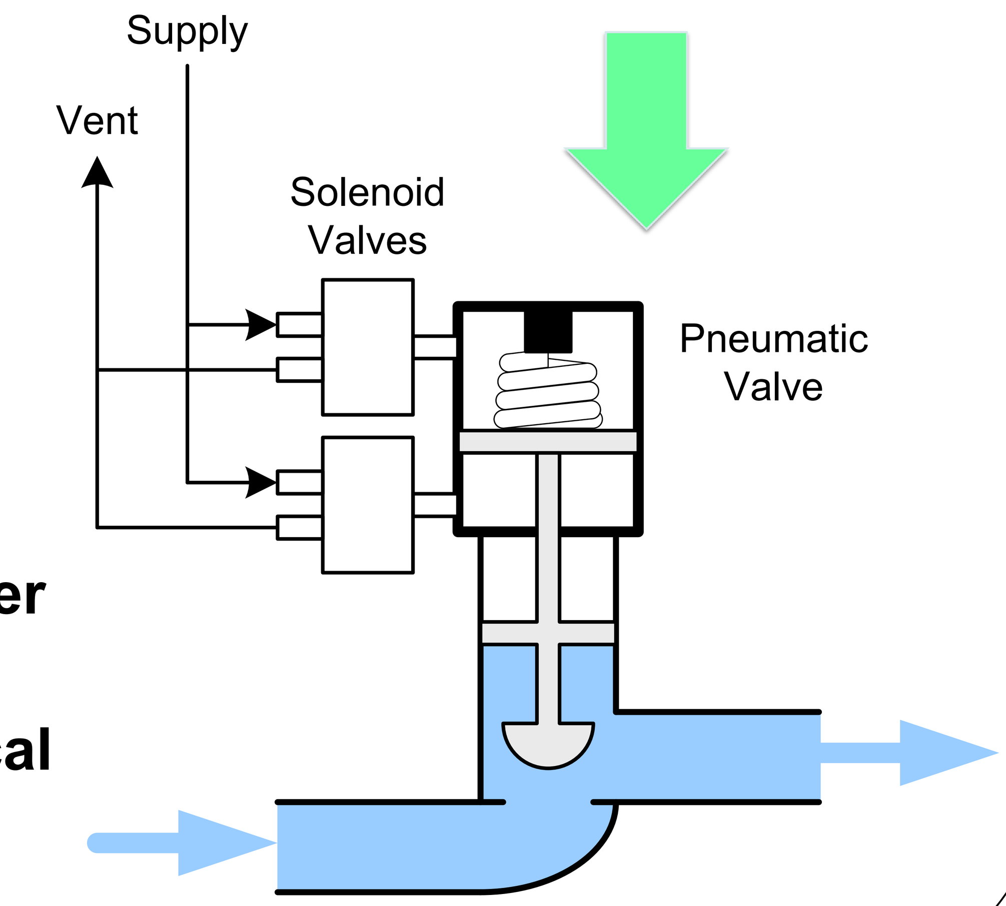
Overview

- **Why physics-based models?**
  - Realistic degradation models provide more accurate life predictions
  - Generate high-fidelity simulation data to test prognosis algorithms
  - Ideal for estimation-based prognosis schemes



- **Solenoid valves**
  - Widely used in many domains, including space and aeronautics
  - Often used in pneumatic systems for actuating other components
  - Complex electromechanical system

Failures may cause loss of redundancy, delay of operations, termination of operations, or vehicle damage



Methodology

First-principles model

Solenoid

$$\dot{i}(t) = \frac{1}{L(x)}\left(u(t) - Ri(t) - i(t)\frac{\partial L(x)}{\partial x}\dot{x}(t)\right)$$

$$F_s(i,x) = \frac{1}{2}i^2\frac{\partial L(x)}{\partial x}$$

Gas flow (subsonic)

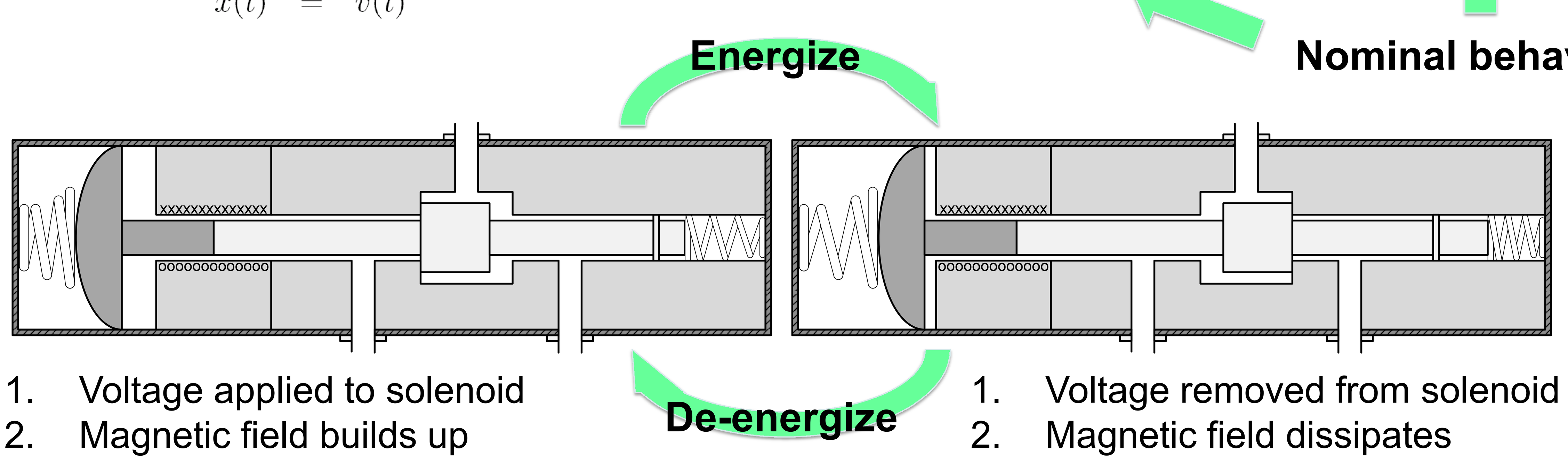
$$\dot{m} = CA\sqrt{2\rho_1 p_1\left(\frac{k}{k-1}\right)\left((p_2/p_1)^{2/k} - (p_2/p_1)^{(k+1)/k}\right)}$$

Poppet

$$\dot{v}(t) = \frac{1}{m}(F_a(t) + F_s(t) + F_{NC}(t) - F_f(t) - F_{NO}(t) - F_r(t))$$

$$\dot{x}(t) = v(t)$$

Nominal behaviors



1. Voltage applied to solenoid
2. Magnetic field builds up
3. Poppet moves right, driven by magnetic force

1. Voltage removed from solenoid
2. Magnetic field dissipates
3. Poppet moves left, driven by return spring

Wear and degradation models

Primary

- **Sliding wear**

  Function of sliding force and velocity

  $$\dot{w}_s(t) = K_s F_f(t) v(t)$$

- **Impact wear**

  Function of impact energy

  $$\dot{w}_i(t) = K\left(\frac{1}{2}mv(t)^2\right)^n \delta(t), t = \text{impact}$$

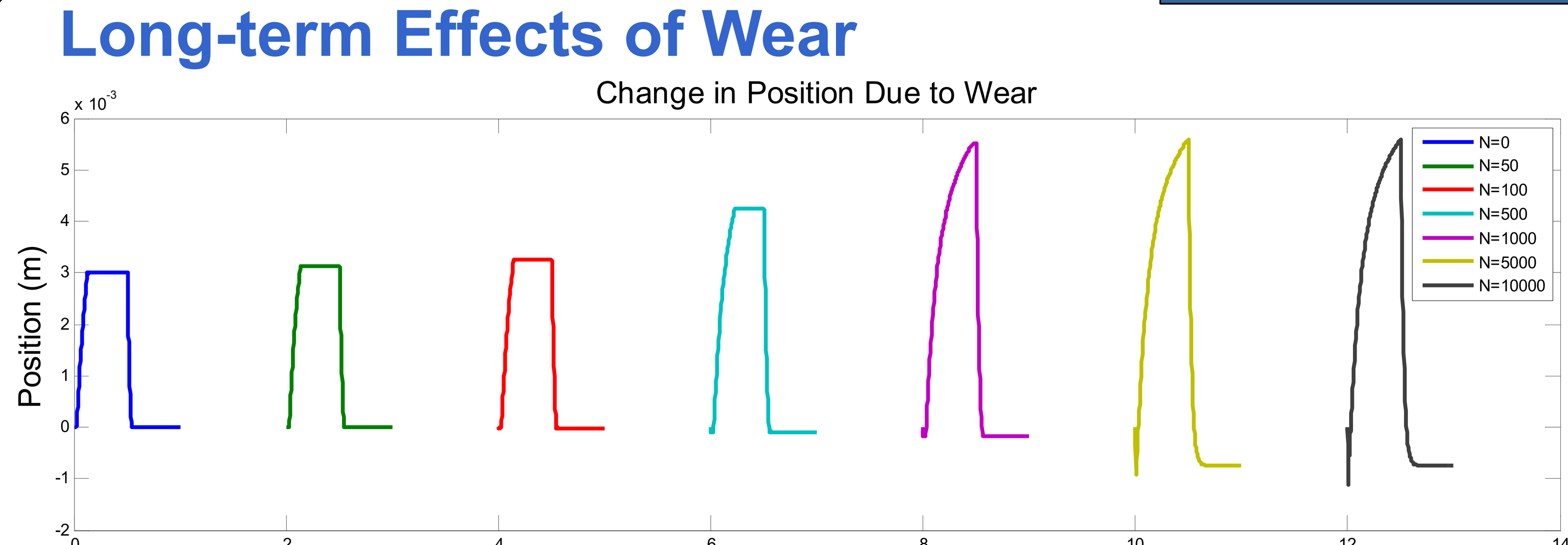
Secondary

- **Coil insulation breakdown**
- **Corrosion**

Change magnetic field
Change force balance
Change gas flow

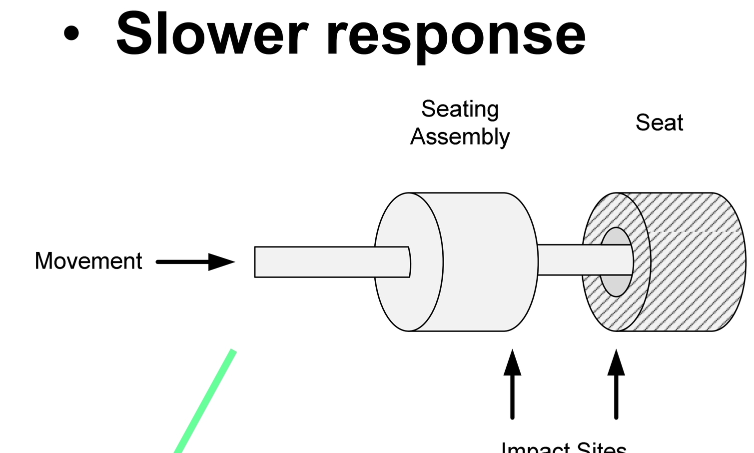
Results

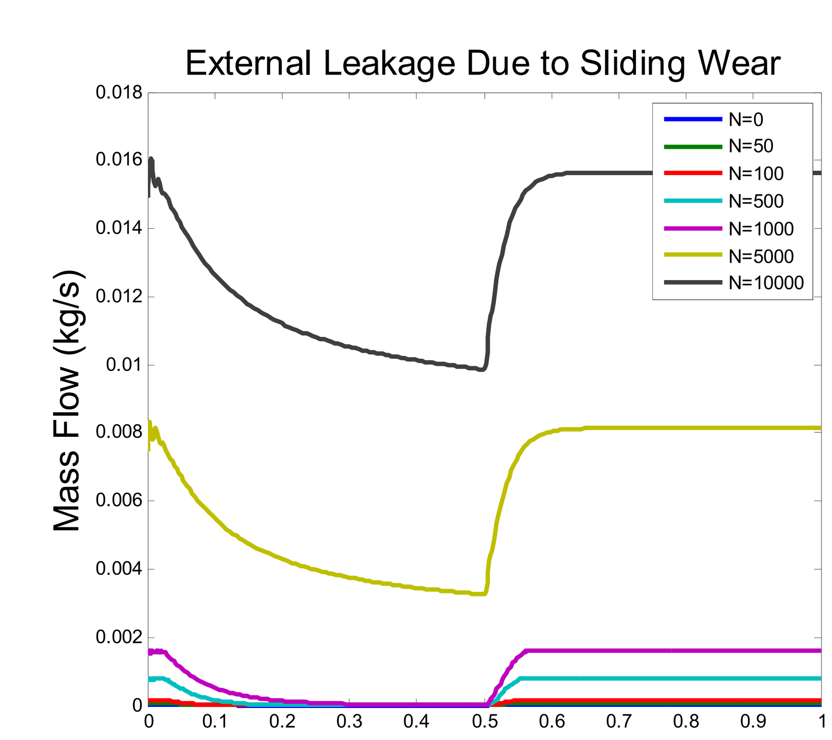
Long-term Effects of Wear

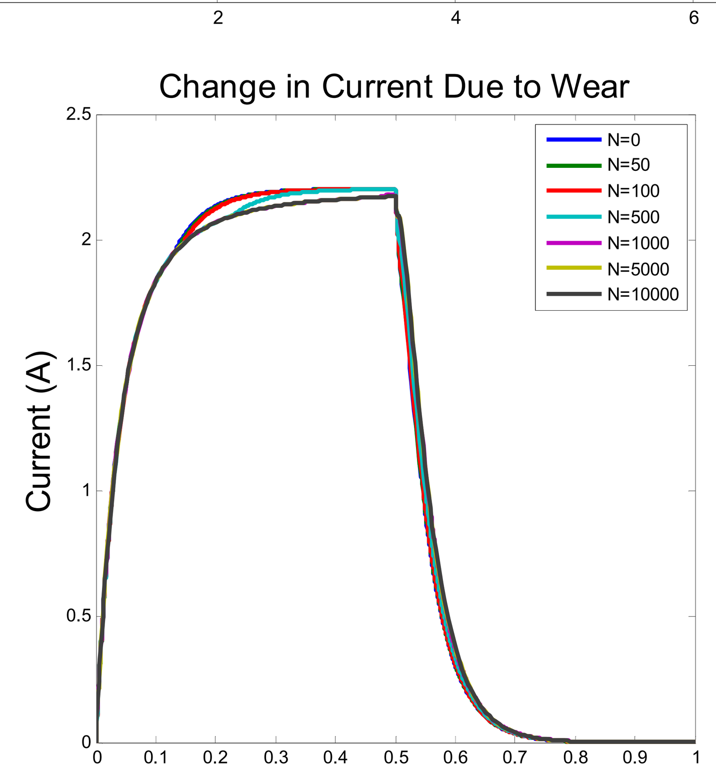


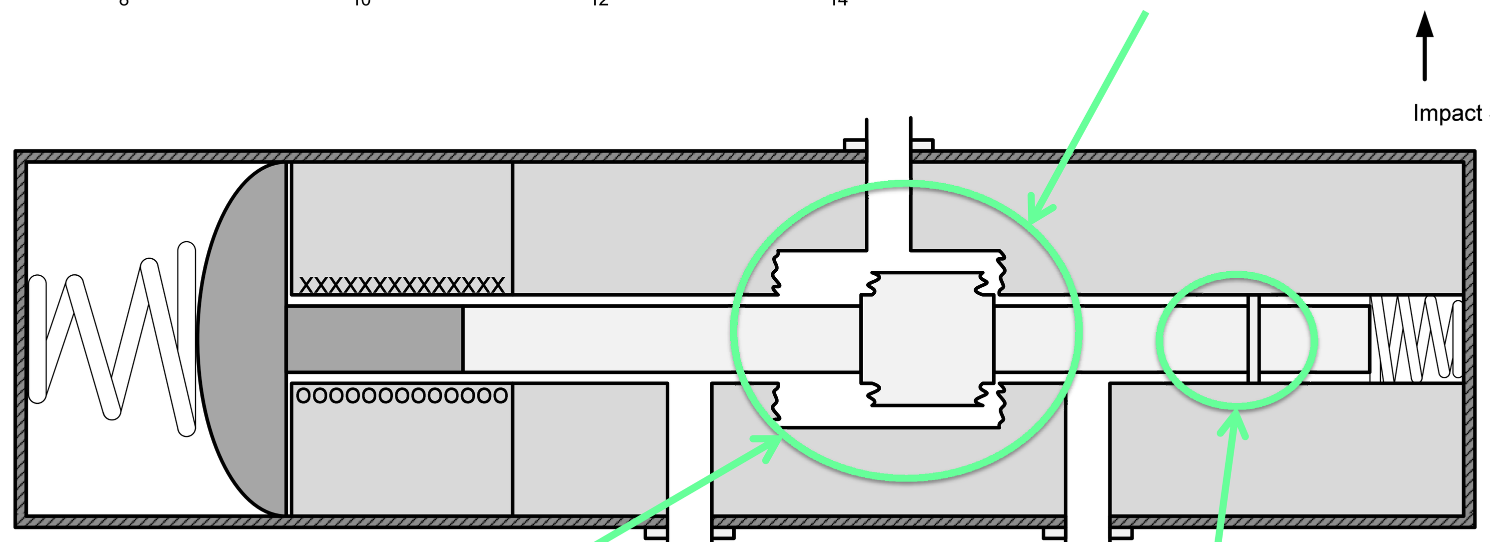
Change in seat geometry results in

- **Incomplete actuation**
- **Slower response**



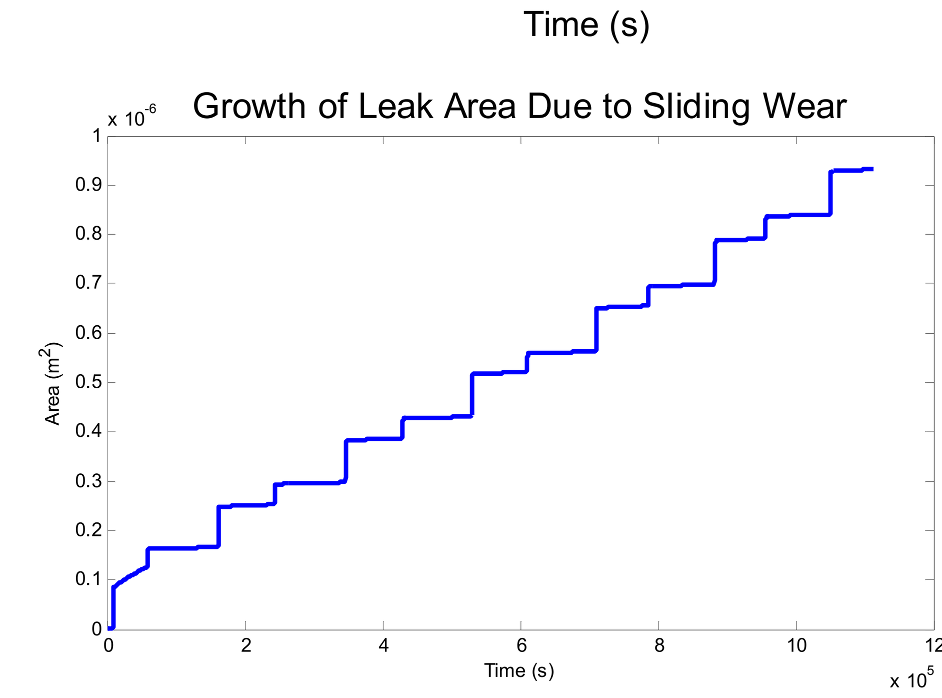






Seat and stem wear due to impact

Leak formation due to sliding wear



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